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Soil & Tillage Research 81 (2005) 227–238
Soil & Tillage Research
www.elsevier.com/locate/still

Effects of potato–grain rotations on soil erosion, carbon dynamics and properties of rangeland sandy soils

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Abstract

The potential for wind erosion in South Central Colorado is greatest in the spring, especially after harvesting of crops such as potato (*Solanum tuberosum* L.) that leave small amounts of crop residue in the surface after harvest. Therefore it is important to implement best management practices that reduce potential wind erosion and that we understand how cropping systems are impacting soil erosion, carbon dynamics, and properties of rangeland sandy soils. We evaluate the effects of cropping systems on soil physical and chemical properties of rangeland sandy soils. The cropping system included a small grain–potato rotation. An uncultivated rangeland site and three fields that two decades ago were converted from rangeland into cultivated center-pivot-irrigation-sprinkler fields were also sampled. Plant and soil samples were collected in the rangeland area and the three adjacent cultivated sites. The soils at these sites were classified as a Gunbarrel loamy sand (Mixed, frigid Typic Psammaquent). We found that for the rangeland site, soil where brush species were growing exhibited C sequestration and increases in soil organic matter (SOM) while the bare soil areas of the rangeland are losing significant amounts of fine particles, nutrients and soil organic carbon (SOM-C) mainly due to wind erosion. When we compared the cultivated sites to the uncultivated rangeland, we found that the SOM-C and soil organic matter nitrogen (SOM-N) increased with increases in crop residue returned into the soils. Our results showed that even with potato crops, which are high intensity cultivated cropping systems, we can maintain the SOM-C with a rotation of two small grain crops (all residue incorporated) and one potato crop, or potentially increase the average SOM-C with a rotation of four small grain crops (all residue incorporated) and one potato crop. Erosion losses of fine silt and clay particles were reduced with the inclusion of small grains. Small grains have the potential to contribute to the conservation of SOM and/or sequester SOM-C and SOM-N for these rangeland systems that have very low C content and that are also losing C from their bare soils areas (40%). Cultivation of these rangelands using rotations with at least two small grain crops can reduce erosion and maintain SOM-C and increasing the number of small grain crops grown successfully in rotation

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0167-1987/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.still.2004.09.010

above two will potentially contribute to C and N sequestration as SOM and to the sequestration of macro- and micro-nutrients.
Published by Elsevier B.V.

Keywords: Carbon sequestration; Erosion; Nitrogen sequestration; Particulate organic matter; Microbial biomass; Soil organic matter; Rangelands

1. Introduction

Continued population growth and increasing demands for natural resources make the reduction of erosion and the development of a sustainable intensive agriculture a priority during the new millennium (Lal, 1995, 2000). Since most of the world's arable land is already under cultivation, we need to continue the development of best management practices that maximize yields while increasing agricultural sustainability (Lal, 2000). Our goal was to conduct an assessment of the effects of potato–small grain rotations on physical and chemical soil properties of cultivated rangeland.

To assess effects of cultivation on rangeland we need to consider the variability in distribution of resources correlated with plant type. Isolated plants can create "island of fertility" or resource islands (Bolton et al., 1990; Halvorson et al., 1992). Smith et al. (1994) reported that microbial biomass-C (MB-C), microbial biomass-N (MB-N), and mineralization were correlated with vegetative cover of semi-arid shrub-steppe ecosystem. To account for this variability we need to assess the brush, grasses and bare soil areas.

Although assessment of brush areas is intensive and labor and time consuming, previously developed techniques can be used to help facilitate the task. Plant biomass production from brush areas have been correlated using dimension and regression analyses of vegetative properties such as stem and crown diameter, crown volume and height by circumferences (Whittaker, 1966; Newbould, 1967; Murray and Jacobson, 1982; Vora, 1988; Hughes et al., 1987).

Barth and Klemmedson (1986) clearly showed the importance of assessing the whole system when evaluating C and N pools of rangeland systems. They found significant changes in amount of N content in the aboveground compartment correlated with soil N availability due to higher mineralization in wetter years. They also reported seasonal aboveground C and N content changes correlated to spring flush growth or to winter plant dormancy. These are some reasons why we need to assess the whole system when studying effects of cultivation on rangeland systems, especially since belowground plant parts and organic compartments are a significant percentage of total N and C (Redente et al., 1989). Redente et al. (1989) reported that approximately 92% of the fixed C in a native shortgrass site of Wyoming was allocated in the belowground compartment.

Parton et al. (1987) divided the SOM-C pool based on its dynamics and residence time into a recalcitrant C pool with longer C turnover times (200–1500 years), a slower pool (20–40 years) and a faster and active pool with turnover times of 1–5 years. Cambardella and Elliott (1992) developed a method to measure the compartmentalization of the SOM-C in particulate organic matter-carbon (POM-C) and organic matter carbon associated with the mineral fraction (OMA-MIN-C). They reported that this POM-C simulated the slower pool and the OMAMIN-C simulated the recalcitrant pool described by Parton et al. (1987).

Aggregates and clay content have been reported to protect SOM from microbial mineralization (Paul and Van Veen, 1978; Van Veen and Paul, 1981; Parton et al., 1987). Tillage can expose protected SOM and increase the rate of decomposition contributing to the decrease of SOM-C levels (Tiessen et al., 1982; Odell et al., 1984; Havlin et al., 1990). Tillage can reduce the POM-C pool in cultivated systems (Cambardella and Elliott, 1992; Hussain et al., 1999). Follett and Schimel (1989) reported that increasing tillage reduced the capability of the soil systems to immobilize mineral N. They found that microbial biomass C and N was higher in native grassland > non-till > plowed systems.

Returning crop residue to the soil can help to maintain SOM (Larson et al., 1972, 1978; Rasmussen et al., 1980; Campbell and Zentner, 1993). Larson et al. (1972) reported additions of residue of 16 Mg ha^{-1} year^{-1} increased SOM by 47%. The amount of corn stalk (*Zea mays* L.) or alfalfa (*Medicago sativa* L.) residue to be added to the soil to maintain the SOM-C levels was 6 Mg ha^{-1} $year^{-1}$ for a silty clay loam. Havlin et al. (1990) found that increases in the amount of crop residue returned to the soil increased the amount of SOM-C and SOM-N. The increases were higher with no till than conventional tillage, but conventional tillage still increased the amount of SOM-C and SOM-N correlated with the amount of crop residue returned to the soil. Another management practice that can increase SOM-C and SOM-N is the addition of N fertilizer that contributes to higher yields, increasing crop residue amounts returned to the soil (Rasmussen et al., 1980; Havlin et al., 1990; Campbell and Zentner, 1993).

The selection of a given crop rotation will impact the quality and quantity of crop residue thus impacting changes in SOM. Several researchers have reported that by including grain crops that have higher C/N ratios in the crop rotation the losses of SOM-C and SOM-N can be minimized (Havlin et al., 1990; Christenson, 1997). Management practices with less soil disturbance such as minimum tillage also contribute to high crop residue accumulation increasing SOM-C and C sequestration (Havlin et al., 1990; Hussain et al., 1999). Cropping systems that reduce potential soil erosion also reduce the losses of SOM-C, SOM-N and other nutrients from the system (Black and Tanaka, 1997; Hussain et al., 1999; Lal, 2000). When compared to fallow systems, increasing cropping intensity has been found to increase the amount of crop residue returned to the soil increasing the amount of SOM-C and SOM-N (Rasmussen and Rohde, 1988; Black and Tanaka, 1997; Peterson and Westfall, 1997).

2. Materials and methods

2.1. Study area

These studies were conducted in a high altitude, intermountain desert valley of South Central Colorado with an average elevation of 2348 m and annual precipitation of 168 mm (Pannell et al., 1973; Edelmann and Buckles, 1984). To evaluate the impact of cropping systems on disturbed rangeland we sampled a rangeland area and three cultivated sites, with similar agricultural practices. These three sites were converted from rangeland into cultivated, center-pivot-irrigation-sprinkler fields two decades ago. The main variability in crop management at these sites has been the amount of straw returned into the surface soil. The USDA-NRCS personnel identified the soils at these sites as a Gunbarrel loamy sand (Mixed, frigid Typic Psammaquent) that is representative of most soils in this region that are of a coarse sandy texture over a coarse textured substratum. They also identified the crop history at the cultivated sites through interviews with farmers.

2.2. Plant biomass sampling

Plant samples were collected in the cultivated areas and in the adjacent rangeland site. The rangeland plant species were black greasewood (*Sarcobatus verniculatus*), alkali sacatone grass (*Sporobulus airoides* Torr.) and bare soils areas with small Kochia (*Scoparia* (L.) *Schrad*) annuals. Plant density covered by greasewood brush was determined by sampling six random 16 m^2 plots. Each plot was marked with a rope and stakes and plant biomass production from brush areas was determined using dimension and regression analyses of vegetative properties such as stem and crown diameter, crown volume and height by circumferences (Table 1; Whittaker, 1966; Newbould, 1967; Murray and Jacobson, 1982; Vora, 1988; Hughes et al., 1987). Plant diameters were measured by using the longest length, then measuring at 90° the

Table 1
Relationship between brush C or N content vs. vegetative brush crown area

Compartment	Nutrient	Regression equation[a]	r^2
Aboveground	C	$y = 0.078x - 340$	0.96^{***}
Surface litter	C	$y = 0.023x - 135$	0.82^{**}
Root	C	$y = 0.020x - 50$	0.89^{**}
Aboveground	N	$y = 0.024x - 10.6$	0.98^{***}
Surface litter	N	$y = 0.001x - 5.5$	0.80^{**}
Root	N	$y = 0.001x - 1.9$	0.87^{**}

Relationship measured for aboveground, surface litter and root compartments on rangeland from South Central Colorado.

[a] y = brush biomass C or N content (g $plant^{-1}$); x = vegetative crown area, measured by using the longest crown diameter, then measuring at 90° the opposite diameter (cm^2 $plant^{-1}$).

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

opposite diameter. The height was also measured for each plant. We sampled four large, four medium and four small sized plants. Surface litter was collected under the brush. Aboveground plant material that was cut at the soil surface with a saw and roots were harvested from the top 0.6 m depths. The best fitted relationship between dimensions analysis and C and N content were used. The equations describing the linear relationship between C or N (g) content per plant and surface area (cm^2) per plant for each plant-compartment are presented in Table 1.

The grass covered areas were minimal and areas were measured with a ruler in each one of the six sampled plots. The aboveground grass biomass was determined by sampling a circle that was 20 cm i.d. Only four grass samples were collected.

The bare soil area was determined by subtracting the brush and grass areas from the total sampled area. The bare soil areas had some small annual Kochia plants and scattered litter. The surface area covered by annuals or scattered surface litter was determined using a line transect 30.5 m long, placing a frame (0.36 m $\times$ 0.61 m) every 3.1 m along the transect with a hit intercept method (USDA-SCS, 1988). All plant material or surface litter in each square was collected.

Rangeland and cultivated sites were sampled during a 2-week period. Samples were brought to the laboratory from the field within 24 h, oven dried at 55 °C for 2 days, ground and analyzed for total C and N content by dry combustion with an automated C–N analyzer (Carlo Erba Strumentazione, 1988[1]). The C and N content for the plant roots, surface litter, and underground litter were corrected for soil contamination using the dry ash procedures described by Clark (1977) and Schimel et al. (1986). To estimate C and N content in the cultivated plant compartments we used average yields and data from Delgado et al. (1998).

Data reported by Delgado et al. (1998) on the average C and N percentage levels for plant compartments and varieties in this region collected across several years and farming systems were obtained. Some of the data reported by Delgado et al. (1998) included plant samples that were collected at CS1, CS2, and CS3. We used the mean values reported across several years by Delgado et al. (1998) to calculate the average N and C content for these cropping systems at harvest.

2.3. Soil sampling

At random we selected four of the six plots previously used for plant biomass measurements. In each one of these four plots we selected at random a medium size brush plant and collected the soil sample at a random direction 0.3 m away from the center of the brush plant. Soil samples under the grass and bare soil areas were collected in the same direction away from the center of the brush. Soil samples were collected under greasewood, grass, and bare soil areas by driving a PVC core (20 cm i.d.) into the soil. Cores were dug out carefully to maintain the soil volume for bulk density measurements. Each soil core was sealed with plastic wrap around both end of the cores and cores were kept in coolers until they were brought into the laboratory, where they were then stored in a refrigerator at 4 °C. All three cultivated sites were in potato when the soil samples were collected. Soil cores were obtained from the midslope of the hill where the tubers were planted. All cultivated soil samples were obtained in the middle of July at the same time the rangeland was sampled.

Cores were processed as soon as possible. Soil water content was measured immediately after taking the cores out of the refrigerator. Soils were sieved through a 2 mm mesh and a subsample was collected immediately and stored again in the refrigerator for microbial biomass analyses. A second soil water content measurement was collected immediately after the sieving was completed. The rest of the soil sample was air-dried, roots and litter removed and the soil weighed. A subsample was sent to Colorado State University Soil Water and Plant Testing Laboratory for texture analyses and P, K, Cu, Mn, Fe, and Zn analyses. Additionally, soil water content at 0.05 MPa was determined.

Total soil organic C was determined by treating a soil sample with 1 M H_3PO_4 acid and running a soil C and N analysis. Soil organic C and N analyses were conducted with a Carlo-Erba analyzer as described

[1] Manufactures and trade names are necessary to report factually on available data, however the USDA or CSU neither guarantees nor warrants the standard of the product; and the use of a given name by the USDA does not imply approval of that product to the exclusion of others that may be suitable.

above. Inorganic N was determined for each sample with two replicate extractions obtained by weighing 20 g of soil, and extracting with 100 mL of 2 M KCl by shaking samples for 1 h, and filtering and shaking the liquid fraction for chemical analysis. Extracts were run for NO_3-N and NH_4-N with colorimetric analysis by a Technicon© autoanalyzer (Bran-Luebbe Analyzing Technologies, 1987). Total soil organic N content was calculated by subtracting inorganic NO_3-N and NH_4-N content from the total N content of the acid treated sample.

2.4. Physical fractionation of the soil SOM

Physical fractionation of soil organic matter was conducted as described by Cambardella and Elliott (1992). Ten grams of subsamples (two acid treated replicates of dry soils) were dispersed in 30 mL of 5 g L^{-1} sodium hexametaphosphate by shaking for 15 h on a reciprocal shaker. The POM was collected on a sieve (53 μm) and rinsed several times with deionized water. The soil slurry passing through the sieve, containing the OMAMIN-C and OMAMIN-N, was dried in a forced-air oven at 50 °C, weighed and ground with a mortar and pestle before the OMAMIN-C and OMAMIN-N were determined. The POM-C and POM-N were determined from the total organic C and N in the soil by the Cambardella and Elliott (1992), where POM-C = total soil organic C in the soil − OMAMIN-C; POM-N = total soil organic N in the soil − OMAMIN-N.

2.5. Microbial biomass

Microbial biomass analyses were conducted as described by Follett and Schimel (1989). Soil samples were first sent to the CSU Soil Water Testing and Plant Laboratory for measurements of water holding capacity at 0.05 MPa. Soil samples were then placed in snap-cap vials and the water content was adjusted to that held at 0.05 MPa with deionized water. Samples were left overnight to equilibrate. Two duplicate samples (50 g) were placed in separate glass containers that were 1.89 L and were made air tight with rubber ring and screw-type lid. Each container had an alkali trap (1 M NaOH) placed in to determine the CO_2 evolution. Samples were incubated in the dark at a constant temperature of 25 °C.

Alkali traps were changed and CO_2 evolution was determined at 10 and 20 days by the chloroform fumigation procedure and equations of Jenkinson and Powlson (1976) and Voroney and Paul (1984). Biomass C and N were calculated using Eqs. (1) and (2), respectively

$$\text{biomass C} = \frac{C_f}{0.41} \tag{1}$$

$$\text{biomass N} = \frac{N_f - N_{uf}}{k_n} \tag{2}$$

where $k_n = [(-0.014)(C_f/N_f) + 0.39]$ and C_f and N_f are the CO_2-C evolved and net NH_4-N released during 10 days incubation for the chloroform (CCl_4) fumigated soil; N_{uf} is the net NH_4-N released during the same 10 days incubation for the unfumigated soil. Chemical analysis in the alkali traps was determined by titration method using standard HCl in the presence of $BaCl_2$.

2.6. Crop history

Personnel from the USDA-NRCS interviewed farmers at these three sites and determined the crop history, including yields. The mean rotation for the most intensive cropping system one (CS1) was 2 years of potato and 1 year of small grain-either wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) (P–P–Gr). The other two systems had small grains crops more often in the rotation with an average of two crops for the Gr–Gr–P (CS2) and four crops for the Gr–Gr–Gr–Gr–P rotation (CS3). All fields applied the best management practices recommended for these areas described by Ristau (1999) with the major differences being the amount of crop residue returned to the soil. Thus over a 20-year period the CS1 rotation would have six grain crops, the CS2 would have 13 grain crops and the CS3 rotation would have 16 grain crops.

Crop residue for CS1 was removed so the average crop residue returned to the soil reflects this transport of C off-site. For CS2 and CS3 the crop residue was incorporated to an approximate depth of 10–12 cm. This was done by deep chiseling the chopped small grain residue into the fields and following with a chisel plow in the fall. Spring tillage involved chisel plowing again and then roller packing. Analysis of variance general linear models and least significant differences mean for completely randomized block design (SAS,

1988) was the statistical tool used to test for difference among brush, grass or bare soil. It was also used to determine mean values for range sites and cultivated sites following the same design.

3. Results and discussion

3.1. Rangeland

The area covered by brush, grass, and bare soil was 59, 1, and 40%, respectively. Although we called the non-brush and non-grass areas the bare soil area, about 15% of the bare soil area was covered by annual and/or surface litter. The total rangeland area covered by vegetation (brush, grass and annuals) or surface litter was 75%. With one quarter of its surface area in bare soil and constantly exposed and unsheltered, the rangeland is susceptible to significant wind erosion which is the main mechanism for off-site transport of fine particles for these uncultivated natural systems.

Table 2 showed that the content of C in aboveground, surface litter and belowground plant compartments was larger in the greasewood (brush) area (Table 2; $P < 0.05$). Of the plant-litter C compartment, the C located in the surface litter and belowground plant compartment was 70, 63, and 91% for the brush, grass and bare soils areas, respectively (Table 3). The lower 63% for the grassland C was because the C in the crowns was reported as part of the aboveground C since due to wind erosion some of the crowns were above the soil surface. Only roots and underground plant litter were allocated in the belowground C compartment. For N, we found that 91, 83 and 91% of the N was compartmentalized in the belowground plant compartments.

Table 2
Aboveground biomass, surface litter and belowground[a] plant C and N grown on brush and grassland and for bare[b] soil of rangeland from South Central Colorado[c]

Compartment (units)	Brush	Grass	Bare soil[b]
Aboveground (kg C ha^{-1})	6370 a	2810 b	158 c
Surface litter (kg C ha^{-1})	1850 a	366 b	547 b
Belowground (kg C ha^{-1})	13030 a	4470 b	1040 c
Aboveground (kg N ha^{-1})	67 a	40 b	5 c
Surface litter (kg N ha^{-1})	70 a	30 b	20 b
Belowground (kg N ha^{-1})	573 a	166 b	34 c

Data within a row with different letters are significantly different at $P < 0.05$.
[a] The belowground plant compartment was the sum of harvested roots and belowground plant litter picked from soil samples.
[b] The bare soil area had a soil cover area due to surface litter or annual plants of 15.0%.
[c] The area covered by brush, grass, and bare soil was 59, 1, and 40%, respectively.

Table 3
Physical and chemical properties for soil (0–0.3 m depth) under brush, grassland and bare[a] areas of rangeland from South Central Colorado

Properties (units)	Brush	Grass	Bare soil[b]
pH	8.6 a	8.6 a	8.7 a
Bulk density (g cm^{-3})	1.2 b	1.2 b	1.3 a
Sand (Mg ha^{-1})	2720 b	2810 b	3090 a
Silt and clay (Mg ha^{-1})	586 b	694 a	611 ab
Silt and clay (%)	18 b	20 a	17 c
P (kg ha^{-1})	64 a	38 b	30 b
K (kg ha^{-1})	3820 a	2920 b	3490 ab
Zn (kg ha^{-1})	4 a	2 b	2 b
Fe (kg ha^{-1})	14 a	11 b	12 b
Mn (kg ha^{-1})	24 a	13 b	9 c
Cu (kg ha^{-1})	5 b	7 a	4 b

Data within a row with different letters are significantly different at $P < 0.05$.
[a] The bare soil area had a soil cover area due to surface litter or annual plants of 15.0%.
[b] The area covered by brush, grass, and bare soil was 59, 1, and 40%, respectively.

Soil pH was about 8.6 and did not differ between areas of brush, grass and bare soil areas (Table 3). Bulk density was lower for the brush and grass, probably due to the effect of higher soil organic matter that can increase aggregates and porosity and can lower soil bulk density (Lal et al., 1999). Additionally, the brush and grass cover areas had lower soil erosion, conserving a higher percentage of fine particles such as silt and clay, particles that are correlated with the protection of SOM and aggregates (Paul and Van Veen, 1978; Van Veen and Paul, 1981; Parton et al., 1987).

There was a larger significant sand content in the bare soil areas with lower percentage of silt and clay, probably due to the fact that soils with over 50% uncovered and unprotected area are highly susceptible to wind erosion. We suggest that wind erosion has been the main mechanism for losses of fine particles and the reason for creating coarser soil textures in bare soil areas when compared to brush and grass covered areas (Campbell and Zentner, 1993; Lal, 1995; Black and Tanaka, 1997; Delgado et al., 1999).

Even though the brush and grass areas had lower bulk densities, they had on average a larger nutrient content than the bare soil (Table 3). The Mn and Cu content in the grass area was higher than the bare soil. The P, Zn, Fe, and Mn in the brush areas were higher than the bare soil. The reason why the brush and grass covered areas had higher nutrients, may be due to the effect of a larger rooting system that can scavenge nutrients from lower depths and deposit them in the surface layer via cycling of root and aboveground plant litter.

3.2. Rangeland soil erosion and C dynamics

There was a significant correlation between the aboveground biomass and surface litter content and the belowground C plant content ($r^2 = 0.99$; $P < 0.05$). The higher plant aboveground biomass content was correlated with SOM-C ($r^2 = 0.90$; $P < 0.13$) and with POM-C ($r^2 = 0.92$; $P < 0.10$). The plant system with larger cycling potential for plant residue C had the larger SOM-C and larger POM-C content. The SOM-C, OMAMIN-C and POM-C were higher from the brush > grass > bare soil (Table 4). We observed that in this non-cultivated rangeland area the areas covered by the grass were patchy, and, in some of these small spots erosion was removing the soil around the grass areas and exposing the patchy grass crowns. This may be one of the reasons of why the OMAMIN-C value for the grass areas was lower than the OMAMIN-C measured for the brush. These data show that for this rangeland site the areas covered with greasewood have larger C sequestration leading to increased soil SOM-C and POM-C content when compared to the grass and bare areas.

Table 4
Fractions[a] of C and N in soil (0–0.3 cm depth) under brush, grassland and for bare[b] soil of rangeland from South Central Colorado[c]

Fractions (units)	Brush	Grass	Bare soil[b]
SOM-C (kg C ha^{-1})	17600 a	14900 b	8600 c
OMAMIN-C (kg C ha^{-1})	12400 a	10400 b	7100 c
POM-C (kg C ha^{-1})	5300 a	3700 b	1500 c
MB-C (kg C ha^{-1})	1200 a	800 b	400 c
SOM-N (kg N ha^{-1})	1770 a	1700 a	1050 b
OMAMIN-N (kg N ha^{-1})	1480 a	1270 a	890 b
POM-N (kg N ha^{-1})	290 ab	430 a	160 b
MB-N (kg N ha^{-1})	240 a	160 b	70 c

Data within a row with different letters are significantly different at $P < 0.05$.

[a] Soil organic matter (SOM); organic matter associated with mineral fraction OMAMIN; particulate organic matter (POM); microbial biomass (MB).

[b] The bare soil area had a soil cover area due to surface litter or annual plants of 15.0%.

[c] The area covered by brush, grass, and bare soil was 59, 1, and 40%, respectively.

The microbial biomass carbon MB-C followed the previously discussed trends with higher content from brush > grass > bare soil. Similarly the SOM-N, POM-N, OMAMIN-N and MB-N mirrors the same compartmentalization of higher contents in the brush > grass > bare soil.

Rangeland soils that are bare and unprotected are losing significant amounts of silt and clay and increasing their sand content due to wind erosion (Table 3). This transport of fine particles due to wind erosion is also removing nutrients and affecting the C dynamics (Table 3). Cambardella and Elliott (1992) reported that the OMAMIN-C simulated the recalcitrant C pool described by Parton et al. (1987) with longer C turnover times (200–1500 years). This recalcitrant OMAMIN-C has been significantly reduced mainly due to wind erosion in the rangeland-bare area (Table 4). Table 4 clearly shows that the rangeland C dynamics is strongly correlated to soil cover, aboveground plant residue input, and off-site transport of soil particles and nutrients due to wind erosion. The brush area with the higher aboveground plant litter residue input and higher belowground root plant C has the highest SOM-C, POM-C, and MB-C. For this rangeland sandy soils that aboveground plant residue and soil cover reduces wind erosion, losses of organic C and nutrients and increases C and N sequestration (Tables 2–4).

3.3. Cropping sequences

Cultivation and irrigation lowered soil pH by about one unit due to the increased release of H^+ from N fertilizers ($P < 0.05$). Besides the application of urea-N fertilizer, the occasional application of sulfuric acid to kill aboveground potato vines, and the application of other agrochemicals capable of lowering the pH, leaching of bases could also be contributing to the lower soil pH. On average, cultivated sites had higher

Table 5
Physical and chemical properties of soil (0–0.3 m depths) from non-cultivated rangeland and different cropping systems after 20 years of cultivation in South Central Colorado

Property	Rangeland	Cropping system		
		CS1	CS2	CS3
pH	8.6 a	7.4 b	7.7 b	7.4 b
Bulk density (g cm^{-3})	1.2 b	1.3 a	1.3 a	1.2 b
Sand (Mg ha^{-1})	2870 c	3600 a	3410 a	3140 b
Silt and clay (Mg ha^{-1})	597 a	477 c	503 b	506 b
Silt and clay (%)	17 a	12 c	13 bc	14 b
P (kg ha^{-1})	50 d	131 b	74 c	168 a
K (kg ha^{-1})	3680 a	1280 b	1300 b	1260 b
Zn (kg ha^{-1})	3 c	11 a	6 b	6 b
Fe (kg ha^{-1})	13 c	40 a	25 b	35 a
Mn (kg ha^{-1})	18 b	28 ab	24 b	38 a
Cu (kg ha^{-1})	5 b	10 a	10 a	9 a

Cropping system rotations were potato–potato–grain (CS1), potato–grain–grain (CS2) and potato–grain–grain–grain–grain (CS3). Data within a row with different letters are significantly different at $P < 0.05$

surface bulk densities than rangeland. The amount of silt and clay was significantly reduced in the cultivated sites. The lower percent of fine particles in the cultivated CS1, CS2, and CS3 could be due to wind erosion that contributed to losses of fine particles and higher sand content (Delgado et al., 1999). The higher sand content may have contributed to the higher bulk densities in the cultivated sites.

Table 5 shows that 120 Mg ha^{-1} or 6 Mg ha^{-1} $year^{-1}$ over 20 years of fine soil particles were lost most probably due to wind erosion for CS1. The fine particle losses for the higher producing crop residue site CS3 were the lowest with about 90 Mg ha^{-1} or 4.5 Mg ha^{-1} $year^{-1}$ over 20 years. Although the estimated losses in fine particles are much lower than the potential losses reported for this region by Delgado et al. (1999), the trend agrees with their data.

On average the nutrient content of the cultivated sites increased ($P < 0.05$; Table 5). The content of macro- and micro-nutrients such as P, Zn, Fe, Mn, and Cu were higher in the cultivated sites than the rangeland. Even though there were significant losses of fine particles from the cultivated sites with potential off-site transport of SOM and nutrients, the net change in nutrient content was positive for the cultivated sites with higher macro- and micro-nutrient content than the rangeland. This higher macro- and micro-nutrient content is a reflection of the addition of agrochemicals and fertilizers. Additionally higher yields of fertilized and irrigated systems and the use of deeper rooted crops that can scavenge nutrients from lower depths and recycle them to the surface soil layer may be reasons for higher nutrients at the cultivated site (Delgado and Follett, 2002). In either case these areas are sequestering macro- and micro-nutrient in the surface soil that can potentially contribute to higher soil fertility and productivity levels. The soil content of Cu, Zn, and Fe for cropping systems increased by at least 200%. Rangeland soil P levels were also increased by at least 50% due to cultivation–fertilization.

Soil K decreased about 66% ($P < 0.05$). Potassium was lowered at a rate of 120 kg K ha^{-1} $year^{-1}$. A significant amount of K may have been lost due to wind erosion and by irrigation leached out of the system or harvested in the grain and tubers. Although during the first 10 years almost no K was added, the last 10 years at these sites has shown regularly banded and occasional broadcast applications of K at rates of 100 kg K_2O ha^{-1}. Since all of these sites received some significant K_2O applications, we suggest that with the predominance of coarse sandy soils a significant amount of losses could be attributed to K leaching. The magnitude of these K losses agree with Delgado and Follett (2002) who reported that most of the K is cycled back to the soil environment and is not retained in a organic compartment.

3.4. Crop rotations and erosion and C dynamics

Carbon dynamics and wind erosion was also correlated to crop residue management practices. Increasing the number of small grain crops grown successfully reduced the losses of wind erosion organic C and increased the sequestration of atmospheric C in the cultivated small grain–potato rotation (Tables 5 and 6). Rotations of P–P–Gr that had lower inputs of crop residue and more time uncovered and protected soil surfaces due to harvesting of crops that leave a small amounts of crop residue had lower SOM-C (Delgado et al., 1999). Table 6, shows that these higher erosion rates are contributing to the removal of SOM-C bound in the recalcitrant OMAMIN-C. Our data agree with Delgado et al. (1999) and with the rangeland soil data presented in Tables 2–4, that showed that keeping the soils covered, using crops with higher crop residue reduces potential losses of soil particles due to wind erosion.

Aboveground crop residue increased from CS3 > CS2 > CS1 (Table 7). The mean C crop residue returned to the soil was highly correlated with the SOM-C and SOM-N content ($r^2 = 0.99$; $P < 0.01$). The mean C crop residue returned to the soil was also correlated with the POM-N ($r^2 = 0.96$; $P < 0.12$). The POM-C increased for the rotations with grain planted over 50% of the time. The OMAMIN-C was correlated with amount of crop residue added to the system and increased with the amount of time that the systems were in small grains. Since the OMAMIN-C is most probably the recalcitrant C pool described by Parton et al. (1987) with larger turnover rates, this reduction in OMAMIN-C is due to wind erosion losses of fine particles and OMAMIN-C. We could use crop residue management and/or crop rotations to reduce wind erosion and increase C inputs and C dynamics of cropping systems (Table 6).

We found that the N fertilizer is being sequestered in the SOM. Even with higher losses of fine particles, the cropping systems that included at least two grain crops had no changes in SOM-N or reported higher SOM-N content. We estimated that about a net increase of 400 kg N ha^{-1} or net increase of 7–20 kg N ha^{-1} year^{-1} can be sequestered in the SOM-N (or POM-N) with cropping systems that have two to four small grains. The POM-N was also increased for CS2 and CS3 (7–12 kg N ha^{-1} year^{-1}). This data suggest that by adding grain and incorporating the crop residue into the soils the POM-N is increased in the systems. This higher N content POM should contribute to increased N cycling and soil quality of these systems.

Small grains were reported to help reduce NO_3-N leaching losses (Delgado, 2001). The inclusion of deeper-rooted small grains contributed to sequester C

Table 6
Carbon and N fractions[a] of soil (0–0.3 m depth) from non-cultivated rangeland and different cropping systems after 20 years of cultivation in South Central Colorado

Fractions (units)	Rangeland	Cropping system		
		CS1	CS2	CS3
SOM-C (kg C ha^{-1})	14000 ab	9580 c	12900 b	15500 a
OMAMIN-C (kg C ha^{-1})	10300 a	7900 b	8880 b	10800 a
POM-C (kg C ha^{-1})	3770 a	1670 b	3980 a	4780 a
MB-C (kg C ha^{-1})	877 a	523 c	671 b	550 c
SOM-N (kg N ha^{-1})	1480 b	1080 c	1480 b	1900 a
OMAMIN-N (kg N ha^{-1})	1250 b	949 d	1100 c	1430 a
POM-N (kg N ha^{-1})	239 c	129 d	372 b	468 a
MB-N (kg N ha^{-1})	172 a	105 b	126 b	98 b

Cropping systems rotations were potato–potato–grain (CS1), potato–grain–grain (CS2) and potato–grain–grain–grain–grain (CS3). Data within a row with different letters are significantly different at $P < 0.05$.

[a] Soil organic matter (SOM); organic matter associated with mineral fraction OMAMIN; particulate organic matter (POM); microbial biomass (MB).

Table 7
Carbon and N fractions at harvest for aboveground plant material, surface litter, harvested crop (grain or tuber), and belowground plant material (roots and or subsurface litter) of non-cultivated rangelands and different cropping systems (20 years average) in South Central Colorado[a]

Compartment	Rangeland	Cropping system		
		CS1	CS2	CS3
Aboveground[b] (kg C ha^{-1})	3870	1700	2160	2540
Surface litter (kg C ha^{-1})	1320	101	96	79
Harvested[b] (kg C ha^{-1})	NA	3320	3480	3300
Belowground[b] (kg C ha^{-1})	8190	1410	2810	1610
Aboveground[b] (kg N ha^{-1})	42	59	40	43
Surface litter (kg N ha^{-1})	50	3	2	2
Harvested[b] (kg N ha^{-1})	NA	158	163	157
Belowground[b] (kg N ha^{-1})	355	56	100	55

Cropping systems rotations were potato–potato–grain (CS1), potato–grain–grain (CS2) and potato–grain–grain–grain–grain (CS3). Rangeland compartments reflects the weighed average of the brush, grass, and bare soil areas.

[a] The area covered by brush, grass, and bare soil was 59, 1, and 40%, respectively.

[b] Aboveground includes the average C and N content in standing biomass at harvest; belowground include roots and subsurface litter at harvest.

and N in the SOM. Delgado (2001) reported that small grains were deeper rooted crops with average depths of 0.6–0.9 m while potato was a shallower rooted crop with average depths of 0.4 m. We estimate that these CS2 and CS3 systems are not in steady state and that about 7–20 kg N from the added fertilizer is being sequestered per ha^{-1} $year^{-1}$. Not only are the small grains contributing to protect water quality by scavenging residual soil NO_3-N potentially available to leach (Delgado, 2001), but they are sequestering N that can also be potentially available to leach. These new findings are very important for modeling of best management practices of potato–small grain systems. We found that the MB-N and MB-C were higher in the rangeland than the cultivated systems (Table 7). This study agrees with Follett and Schimel (1989) which also reported higher MB-C and MB-N in the non-cultivated areas.

Larson et al. (1972) reported that about 6 Mg ha^{-1} $year^{-1}$ of corn residue was needed to maintain the SOM-C. Assuming a 40% C content, we need to add about 2.4 Mg C ha^{-1} $year^{-1}$ of high C/N grain straw residue to maintain SOM levels. Our data agrees with Larson et al. (1972) studies. When we added about 2.5 Mg C ha^{-1} $year^{-1}$ with the small grain crop residue for CS3 we increased the level of SOM for these coarse sandy soils. For CS2 we added about 2.1 Mg C ha^{-1} $year^{-1}$ that contributed to maintain the SOM-C levels. The amount of C added of 1.7 Mg ha^{-1} $year^{-1}$ of grain with CS1 was lower than those levels reported by Larson et al. (1972) and we observed significantly larger losses of SOM-C.

The sum of C in the aboveground, surface litter and belowground plant compartments for CS1, CS2 and CS3 was about 24, 38, and 32%, respectively, of the C content measured for the rangeland (Tables 2 and 7). The rangeland plant compartment serves as a larger C storage pool, especially for the hardy, wood brush plants. The rangeland plant C pool has three or four times the C in the plant compartment than that of the cultivated systems.

If we account for the average C sequestered in the grain or tuber, we still have lower C in all plant compartments at harvest for CS1, CS2 and CS3 of about 49, 64, and 56%, respectively, of the C content measured for the rangeland. To balance the C in the plant we will have to harvest and store about 3 years of production to have the same amount of C that was initially present in the plant C pool. The discussion of the fate of all harvested and/or transported C over the last two decades of cultivation is beyond the scope of this paper.

4. Summary and conclusions

This study suggests that greasewood, the dominate species in this rangeland can potentially contribute to C sequestration. Greasewood areas had higher nutrient levels especially for C and N levels. These data suggest that wind erosion adds to losses of C, N, other nutrients and fine particles and that it is also contributing to the reduction of the area covered by grass. We suggest that although the brush areas (59%) are sequestering C, the bare soil areas (40%) are losing C and fine soil particles.

Our study was designed to evaluate this site assuming that today's C, N and nutrient levels in the rangeland simulate those of two decades ago. We acknowledge that since we do not know if the rangeland system is steady state or if it is losing or gaining C and N or nutrients, our comparison may not represent how cultivation has changed the soil chemical and physical properties, when compared to non-cultivated rangeland two decades ago, but instead represents how cultivation has changed the system to today's non cultivated rangelands.

Table 6 shows that there was a positive increase (C sequestration) for SOM-C with increases in crop residue ($r^2 = 0.99$; $P < 0.01$). We observed no net changes in rangeland soil SOM-C due to cultivation for CS2 (slight average reduction) and CS3 (slight average increase). We found that for this potato–small grain system the SOM-C was significantly correlated with the amount of crop residue that was added into the system. These results are in agreement with other scientists who found that increasing crop residue incorporation into the system increases SOM-C (Larson et al., 1972, 1978; Rasmussen et al., 1980; Havlin et al., 1990; Campbell and Zentner, 1993; Christenson, 1997). Crop rotations with higher residue inputs can also increase SOM-N for these potato–small grain systems. These results agree with previous findings that N fertilizer inputs can contribute to increases in N in the SOM (Rasmussen et al., 1980; Havlin et al., 1990; Campbell and Zentner, 1993).

Our study shows the importance of crop residue management for potato–small grain systems. There is potential to use crop rotations as tools to maintain the sustainability of agricultural systems, especially for systems that include shallower and low production crop residue, as long as we incorporate small grain crops with high C/N ratios (Delgado et al., 1998). We could use the inclusion of small grain in this intensive potato–small grain rotations to conserve soil quality. This universal tool (crop rotations) can be used to reduce the potential wind-erosion, losses of fine silt and clay particles, to sequester C, N and other macro- and micro-nutrients. These properties are related to soil fertility and productivity levels. Crop residue management and C dynamics practices reduce wind erosion and increase C sequestration and soil fertility of cultivated potato–small grain systems.

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